SOURCE REGIONS OF THE SLOW SOLAR WIND

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## ABSTRACT

While the fast solar wind is generally thought to originate from coronal holes, the source of the slow solar wind is only known to be associated with the highly structured and highly variable streamer belt. There is growing evidence from multiple-station intensity scintillation measurements of solar wind velocity — usually referred to as IPS for interplanetary scintillation— that the slow wind originates in localized regions of the solar corona overlying the streamer belt. In this paper, velocity structure in the corona is investigated based on velocities deduced from the power spectra of single-station intensity scintillation measurements carried out by Voyager 2 during its solar conjunctions in 1979 and 1982 using its S- and X-band (13 and 3.6 cm wavelengths, respectively) radio signals. As in previous IPS studies, low speed wind is observed. Unlike previous studies of the inner corona, simultaneous estimates of density fluctuation from the same intensity scintillation measurements are available to provide the context for the Voyager 2 velocity measurements. Prominent enhancements in density fluctuation characterizing streamer stalks are found to coincide with the low speed wind, leading to the first observational evidence that streamer stalks are the long sought sources of the slow solar wind.

## INTRODUCTION

Decades of exploring the three-dimensional inner heliosphere by direct spacecraft measurements have shown that the solar wind can be grouped roughly into low- and high-speed flows with distinctly different plasma properties, suggesting different coronal origins [*Hundhausen*, 1977; *Schwenn*, 1990]. While the fast wind is generally thought to come from coronal holes, the slow wind is known only to be associated with the highly structured and highly variable streamer belt [Gosling, 1997].

There is growing evidence from multiple-station intensity scintillation measurements of solar wind velocity — often referred to as IPS measurements for interplanetary scintillation — that the slow wind emanates from localized sources in the corona overlying the streamer belt. The steep velocity gradients inside 10 R. deduced from centimeter wavelength IPS measurements conducted at the VLA in 1983 suggest this [*Woo*, 1995]. Synoptic maps of velocity based on meter wavelength IPS measurements near solar minimum reinforce it by revealing an apparent tendency for the broad band of low-speed solar wind beyond 0.3 AU to breakup into islands of slow wind inside 0.3 AU [*Kojima et al.*, 1992].

White-light measurements show that coronal streamers taper to narrow extensions or stalks of angular size 1-2° by a few solar radii with increasing heliocentric distance [see e.g., *Koutchmy*, 1977]. These stalks comprise fine-scale structures that are strikingly pronounced when compared with the rest of the quiescent solar wind, and produce distinct and conspicuous enhancements in radio occultation measurements that sense density fluctuation [Woo *et al.*, 1995a; *Woo and Habbal*, 1997a]. Recent advances in characterizing streamer stalks suggest that they are the likely localized sources of the slow solar wind. First, they encompass the heliospheric current sheet, as demonstrated by the reversal of coronal magnetic field within them [Woo, 1997]. Second, they appear in solar wind measurements beyond 0,3 AU as heliospheric plasma sheets, with decreases in helium abundance that appear to coincide with the plasma sheet boundaries [*Bavassano et al.*, 1997].

Most investigations of the solar corona based on radio occultation measurements have focused either on velocity (as those mentioned above) or density fluctuation. The ability of radio occultation measurements sensing density fluctuation to detect streamer stalks means that, when conducted at the same time as velocity measurements, they can play a crucial role in the study of the source of the slow wind, because they provide the heretofore missing context for the velocity measurements.

The purpose of this paper is to carry out the first comparison between simultaneous measurements of mean velocity and density fluctuation in the inner corona. These measurements, deduced from Voyager 2 S- and X-band (wavelengths of 13.6 and 3.6 cm, respectively) intensity scintillation measurements during 1979–1982 by ***Martin*** [1985], provide the first observational evidence that streamer stalks are the long sought sources of the slow solar wind.

## VOYAGER 2 RADIO OCCULTATION MEASUREMENTS

Intensity scintillation, spectral broadening and phase scintillation measurements were conducted by *Martin [1985]* using the Voyager 1 and 2 S- and X-band radio signals during the solar conjunctions of the two spacecraft in 1979–1982. Theoretical intensity scintillation spectra — based on a thick-screen model for weak intensity scintillations that included the effects of a random velocity distribution and anisotropic electron density irregularities — were compared with measured intensity spectra to obtain least squares estimates of mean velocity $V_o$. Comparisons between velocities inferred from this method with those from the more common multiple-station correlation technique have been made by *Manoharan and Ananthakrishnan [1990].* Electron density fluctuation $\sigma_{ne}$ was also estimated by integrating the spectrum of the density fluctuations over the range of spatial wavenumbers probed by the intensity scintillation measurements, typically 5 x $10^{-4}$ $km^{-1}$ to 1 $km^{-1}$. These density fluctuations represent mostly the turbulence flowing through flux tubes, but can include crossings of the flux tubes [Woo *and* ***Habbal,*** 1997b]. Details of the inversions of V. and $s_{ne}$ are given in ***Martin*** [1985].

Shown in Figure 1 are the plasma results obtained during the 1982 Voyager 2 (left panels) and 1979 Voyager 2 (right panels) superior conjunctions. The upper panels are of mean velocity $V_o$, and the lower panels are of density fluctuations referred to 1 AU assuming that the fluctuations vary with the inverse square of heliocentric distance, i.e., normalized $s_{ne}$. The abscissas of the plots of $\sigma_{ne}$ and V. are graphically represented by the spacecraft tracks shown between the plots, which have the virtue of showing simultaneously the heliocentric distance and solar latitude of each measurement. The tracks are in the plane of the sky with the Sun drawn to scale. The spacecraft positions along the tracks are indicated by tick marks corresponding to 0000 hours GMT each day, with day numbers of the first and last days shown at the left and right ends of the plotted track. The abscissa of each data point corresponds to the position of the spacecraft along its track at the time of the measurement, indicated by a filled triangle. A few corresponding heliocentric distances are indicated along the tops of the velocity plot panels.

The mean velocity estimates shown in Figure 1 were obtained from an analysis of intensity scintillation spectra for different values of axial ratio of the anisotropic electron density irregularities. Angular broadening measurements have shown that electron density irregularities near the Sun are anisotropic [see e.g., Armstrong et al., 1990], a consequence of the manifestation of the smallest flux tubes [Woo, 1996; *Woo* ***and Habbal,*** **1997b].** The same axial ratio is assumed for all points on a connected curve, with the lowest curve corresponding to 1.0 (isotropic irregularities), the next highest to 2.0, and so on. There is an interdependence between axial ratio, random component of velocity, and mean velocity in the interpretation.of intensity scintillation spectra **[*Martin*,** 1985], and we have neglected the velocity fluctuation. Although the uncertainties of the velocities as indicated by the vertical error bars appear small, it should be emphasized that they are estimated under the assumption of fixed axial ratio and zero velocity fluctuation. Our interest here is in relative change of the morphology the corona, and axial ratio and velocity fluctuations are not expected to significantly affect the relative changes in velocity inferred from the intensity scintillation measurements.

Although sparser than the 1983 VLA measurements used to demonstrate velocity structure [Woo, 1995], the velocities in Figure 1 for the 1982 Voyager 2 conjunction (left panel) still exhibit large gradients and extremes similar to those observed in the VLA measurements. As in the VLA measurements, the observed variations represent mainly structure (variation with latitude and longitude) rather than acceleration of the solar wind (radial dependence). Unlike the VLA measurements, simultaneous measurements of density fluctuation are available. When the velocity minima, marked as features A and B, are compared with the density fluctuation measurements, they are found to coincide with the peaks in density fluctuation, consistent with their locations being within streamer stalks. Further support is provided by the fact that features A and B are located near the heliospheric current sheet (neutral line) as shown in the corresponding source surface magnetic field map [*Hoeksema and Scherrer*, 1986] in the upper panel of Figure 2. They also overlie streamers observed in the low corona as seen in the corresponding white-light synoptic maps reproduced in Figure 3 from *Rocket al. [1983],* and based on measurements made by the HAO Mauna Loa Mark III K-coronagraph *[Fisher et al.,* 198 1]. Although the emphasis in this paper is on the sources of the slow wind, it is interesting that, as expected, conspicuous increases in velocity that are accompanied by similar decreases in density fluctuation are observed by Voyager 2 over the north coronal hole during the 1982 solar conjunction (feature C). Since feature C spans a region of high latitudes including the north pole near CL130° that is far away from the neutral line and streamers, it is not shown on the maps in Figures 2 and 3.

The minimum of the 1979 Voyager 2 velocity measurements displayed in the upper right panel of Figure 1 is marked feature D. Although the rapid rise in velocity with radial distance may at first glance seem to represent acceleration of the solar wind, the fact that the level of $\sigma_{ne}$ corresponding to feature D is conspicuously high (factor of 3 higher than the minimum) and comparable to that of feature B in the 1982 measurements suggests that feature D is also likely a streamer stalk. This interpretation is strengthened by the close proximity of feature D to the neutral line shown in the source surface magnetic field map in the lower panel of Figure. 2. Unfortunately, white-light measurements of the lower corona were not available during the 1979 measurements. Phase scintillation and spectral broadening measurements corresponding to the time of feature D have also been used in an earlier investigation of the density spectrum to infer that the filamentary structures are finest in the slow solar wind associated with coronal streamers [Woo *and Habbal*, 1997b]. Like the 1982 measurements, the highest velocity observed in the 1979 measurements is located in the vicinity of lowest $\sigma_{ne}$ and far from the heliospheric current sheet, as seen in the source surface magnetic field map in the lower panel of Figure 2 (feature E).

## CONCLUSIONS AND DISCUSSION

Like the 1983 VLA measurements *[Armstrong et al.,* 1986] analyzed earlier [ *Woo,* 1995], large gradients and extremes in velocity are observed in the 1979 and 1982 Voyager measurements. However, unlike the VLA velocities, there are simultaneous measurements of density fluctuations to provide the crucial context for the Voyager velocity measurements. These not only show that the relative velocity changes represent mainly latitudinal and longitudinal variations rather than radial dependence, they also show that the lowest velocities: (1) coincide with the highest levels of density fluctuation, (2) are found near the heliospheric current sheet, and (3) when white-light measurements are available overlie coronal streamers. Since prominent enhancements in density fluctuation characterize coronal streamer stalks, the results of this study provide the first observational evidence that streamer stalks are the long sought sources of the slow solar wind. Such a conclusion is possible in spite of the sparsity of the Voyager 2 measurements because they fortuitously took place within streamer stalks, as indicated by the conspicuous enhancements in $\sigma_{ne}$. While measurements during other conjunctions of both Voyager 1 and 2 *[Martin,* 1986] hint at similar results, the streamers were not as well observed.

Radio occultation measurements have been used for decades to investigate the corona, but only recently has the extent to which the corona is structured been revealed by these measurements, and only recently has information on the morphology of the corona, which could be related to features observed in white-light and in situ measurements beyond 0.3 AU, been obtained from such measurements. Although velocity, density fluctuation and density have all been widely observed, the aforementioned advances have come from the measurements of density fluctuation and density (rather than velocity) because these plasma parameters are observed more directly. For instance, raylike structures are more readily revealed in measurements of path-integrated density and its derivative (ranging and Doppler, respectively), as strikingly demonstrated in white-light images [*Koutchmy*, 1977]. The finest structures are also revealed in the anisotropy of the density fluctuations observed by angular broadening or angular scattering measurements [*Woo*, 1996; *Woo and Habbal*, 1997b].

Compared with density, velocities deduced from single- or multiple-station IPS measurements are more indirect. The velocities and their uncertainties are more dependent on the interpretation of the radio scattering observations and modeling of the solar wind [see e.g., *Grail, 1995; Klinglesmith, 1997*]. The ability to distinguish stalks (associated with the slow wind) from coronal holes (fast wind) based on radio occultation measurements of density fluctuation surpasses that of multiple-station IPS measurements to separate fast from slow solar wind. In fact, the latter is also dependent on the separation of the baselines of the observing stations, as recently demonstrated by *Grail et al.* [1996]. For these reasons, unlike radio occultation measurements of density and its derivative, IPS measurements are limited to investigating large-scale velocity structure.

The demonstration in this paper that the fast wind is characterized by low $\sigma_{ne}$ is as important as showing that the slow wind is associated with high $\sigma_{ne}$. This result reinforces the emerging global view of the quiescent near-Sun solar wind based on measurements of density fluctuation alone — that streamers occupying a small fraction of volume in interplanetary space, and representing sources of the slow wind, are superimposed on a background corona distinguished by raylike structures that are the sources of the fast wind [*Woo and Habbal*, 1997a] — because low values of $\sigma_{ne}$ are strikingly ubiquitous [*Woo and Gazis*, 1994; *Woo and Habbal,* 1997a], even during the high portion of the solar cycle [*Woo et al.,* 1995 b]. The Voyager measurements add to this picture since they took place during the high portion of the solar cycle, suggesting that slow solar wind flows from the stalks or extensions of coronal streamers thoughout the solar cycle. In this global view, fast rather than slow wind would be expected to predominate the quiescent solar wind during the upcoming high activity portion of the solar cycle when Ulysses makes its next polar passages. Although radio occultation measurements of velocity may suggest otherwise [*Coles*, 1995; *Gosling, 1997*], the limitations in separating slow from fast wind, especially at a time when the corona is dominated by streamers, may be presenting a misleading picture.

It is clear that the study of large-scale velocity structure would benefit from additional IPS measurements. However, if further progress is to be made, future IPS measurements need to be conducted either jointly with radio occultation measurements sensing density fluctuation in order to define the context of the velocity measurements or white-light measurements. One of the reasons that the connection between slow wind and coronal stalks was not made in previous comparisons between IPS and coronal white-light measurements is that the white-light measurements often did not extend far enough in solar distance to reveal the streamer stalks. Such is not the case with LASCO on SOHO [*Brueckner et al.*, 1995], which offers new opportunities for comparisons with radio occultation measurements out to 30 $R_o$. Future IPS measurements of velocity should also be made as continuously as possible to provide the spatial coverage necessary for revealing exciting new details of the source of the slow solar wind.

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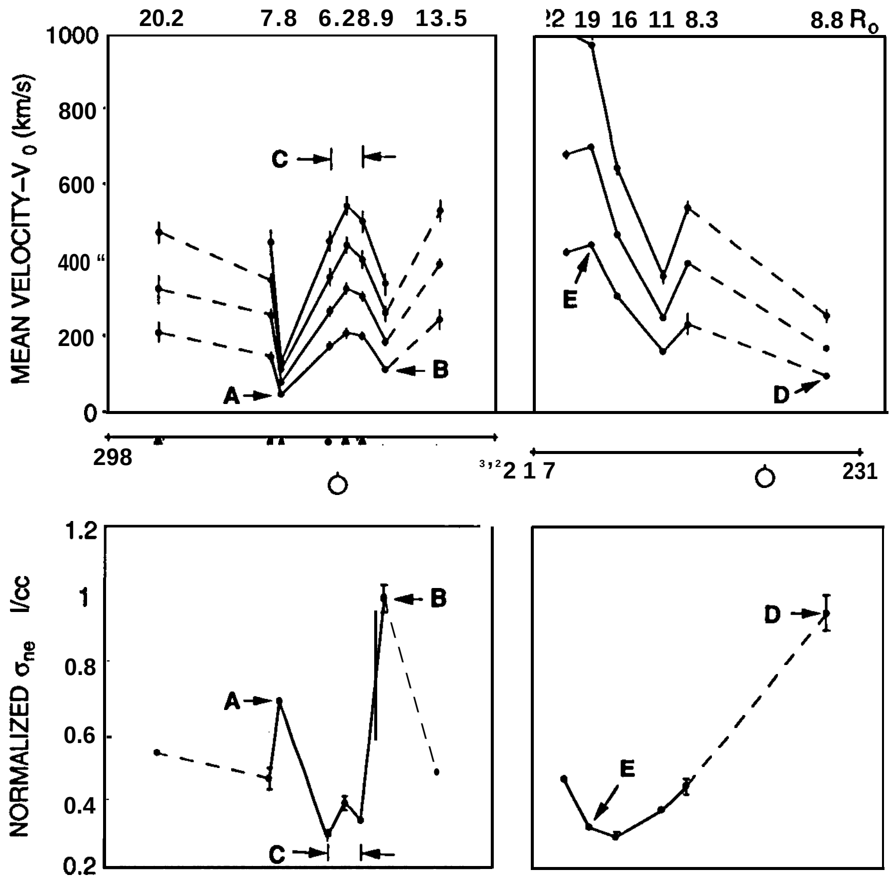
## FIGURE CAPTIONS

Figure 1 Mean velocity $v_o$ (upper panels), density fluctuation $\sigma_{ne}$ normalized to 1 AU assuming an inverse square of heliocentric distance dependence (lower panels). The abscissa is represented graphically by the track of the spacecraft shown between the upper and lower panels. Tick marks are 0000 UT for each day in the range of day numbers indicated by the numbers at the ends of the tracks. The solid triangles are the abscissas of the measurements. The left (right) panels are for the 1982 Voyager 2 (1979 Voyager 2) solar conjunction. Dashed line indicates a large region for which no measurements were made. The numbers at the top of the upper panels are corresponding heliocentric distances.

Figure 2 Source surface magnetic field maps from Hoeksema and Scherrer [1986]. The slowest wind (features A, B and D in Figure 1) is associated with coronal streamer stalks as identified by their enhanced levels of $\sigma_{ne}$, and is generally located near the neutral line. The fast wind (feature E) associated with low levels of $\sigma_{ne}$ is located far from the neutral line.

Figure 3 HAO Mauna Loa Mark III K-coronameter synoptic contour maps of polarized brightness pB at a height of 1.7 R. from *Rocket al. [1983]* based on east limb (upper panel) and west limb (bottom panel) measurements. The white dots, corresponding to the locations of features A and B in Figure 1 and the apparent source of the slow wind, overlie coronal streamers,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NORMALIZED $\sigma_{ne}$ l/cc

Figure 1

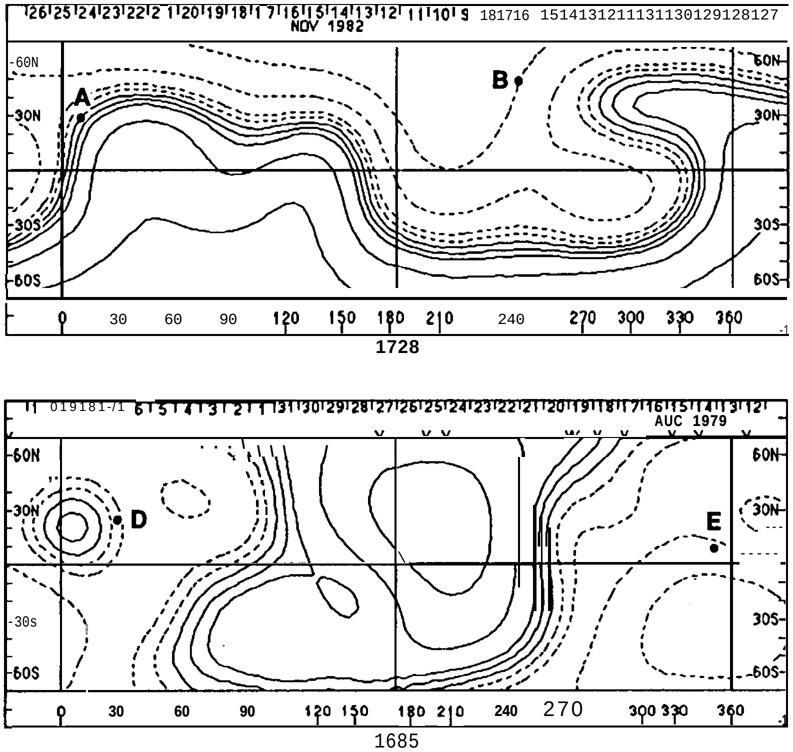
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Fig. 2

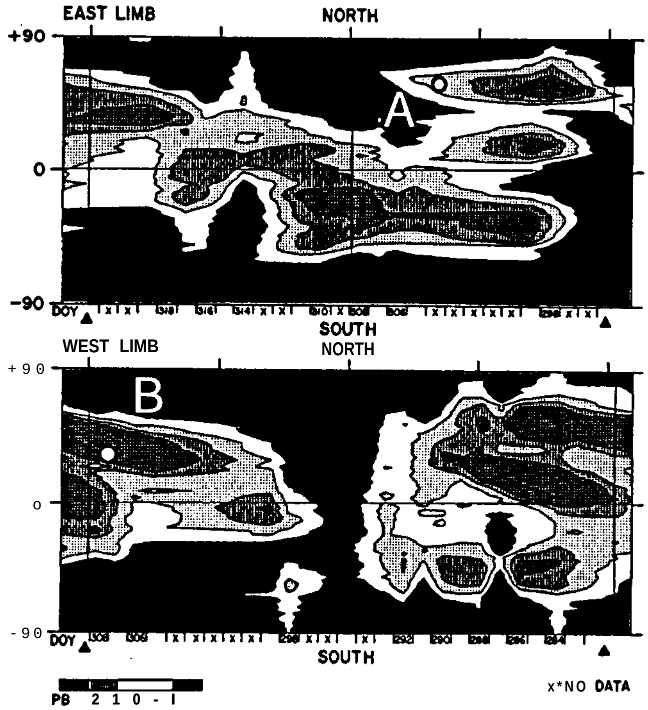
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Figure 3